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Failure Analysis of Refractory Anchors of a Power Boiler

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Abstract

The present study analyse the refractory structure failure in the bull nose - hot face area of cyclone of a circulating fluidised bed combustion (CFBC) boiler. Failed anchor rods made of AIS309 SS were analyzed for chemical composition, hardness, tensile strength and microstructural condition. Sigma (s) phase induced embrittlement caused failure of anchor at the non-welded end. At the anchor-MS plate weld, poor quality of the weld was noted. Overheating from flue gas entry in the gaps caused by inadequate expansion joints resulted in damage to the backup insulation layers. At such high temperatures, the SS anchor-MS weld will have a lesser strength and weld failure occurred. Loss of anchor reinforcement resulted in falling of refractories.

Keywords: Refractory anchor; AIS309 SS; Sigma phase; Weld failure

1. Introduction

Refractory structures used in power boilers use stainless steel anchors for reinforcement. Failure of refractories in the form of cracks leading to falling off them were observed in operation. Often the refractories themselves are not the cause of failure rather the reinforcing metallic anchors were found to be the one [1-3]. Wrong choice of material, inadequate design of refractory structure, over temperatures leading to anchor material deterioration are among the main reasons for anchor failures. A thermal power plant using circulating fluidised bed combustion (CFBC) technology in the boiler to raise steam reported refractory blocks failure in the bull nose-hot face area of cyclone separator with AISI 309 stainless steel (SS) alloy anchors broken & sheared even as the refractories looked good in condition. The present report describe the details of failure analysis investigation for the same

2. Technical Background

Failed section consists of 800x600x120mm panels of castable refractory with backup insulation of 280mm

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with metallic anchors of AISI309 SS grade welded to mild steel (MS) plate, for reinforcement. Service temperature at the hot face area was 800^{o}C (max.). Total service period for anchors is 3 years. Total numbers of shutdown in 3 years is 35. Of these 17 are within 4 months period preceding failure. Two blocks / panels of refractory were lying inside the furnace bull nose - hot face area with no damages like surface cracks, edge cracks and corner cracks even after falling from 25m height. Some anchors were found to have straightened instead of the curved shape and with oxidation, elongation and erosion features on the surface and some embedded anchors were observed with sharp edges from shearing.. Plant also reported buckling of outer shell at the failed location with damage to the backup insulation. Two anchor pieces - one service exposed and failed and another unused (hereinafter referred as unexposed) were submitted for metallurgical failure investigation.

3. Visual Examination

Photographs of the anchor rods under investigation were shown Fig.1. Unexposed anchor (7.85mm dia.) and the surface appeared with smooth finish. Failed anchor rod (9.85mm dia.) appeared with erosion marks left by the hot fluidised process media and discoloured due to oxidation but it was not severe as shown by presence of thin layer of scale. The non-welded end of the failed anchor rod showed a flat fractured face. Few circumferential cracks were seen in this side of anchor rod. The flat fracture face might have been from one such crack.

Fig.1 Photographs of the unexposed and service exposed anchors

4. Experimental and Results

4.1. Chemical Analysis

Failed and unexposed anchors were analysed for chemical composition. Inductively coupled plasma spectrophotometer was used for the analysis of metallic elements and LECO make carbon-sulphur analyzer was used for estimation of carbon and sulphur levels. Obtained results were presented in the following Table 1. Observed chemical composition showed that chromium(Cr), nickel(Ni) and manganese (Mn) levels were lower and silicon (Si) is marginally higher than the specified range for AISI-309 SS.

4.2. Hardness

Sample pieces of service exposed/failed and unexposed anchor rods were cut and tested for hardness value. A load of 300 grams was applied and a dwell time of 10 seconds was given. Observed results presented in Table 2 were average value of five readings. Observed values clearly indicates, hardness level of failed anchor rod is higher compared to unexposed anchor rod.

4.3 Tensile Strength

Sample piece of anchors was not suitable for making standard size tensile test specimens. As such, tensile strength at room temperature was assessed using sub-size specimens. Observed results were presented in Table 3. Observed values indicate that failed anchor and unexposed anchor met the specified strength levels. The ductility in terms of percentage elongation and percent reduction area got significantly affected for service exposed anchor compared to the unexposed one.

4.4 Metallography

Standard metallographic specimens were cut, polished and finished with diamond polish and etched with aqua regia (3:1mix of Cl and HNO_3). To reveal sigma phase (s), a specific electrolytic etchant solution of 20gm sodium hydroxide (NaOH) in 80ml of water, at an applied voltage of 3V for 60 seconds was used.

4.4.1. Optical Microscopy

Optical micrographs of unexposed and failed anchors were shown in Fig. 2. Observed microstructure is typical of a austenitic stainless steel. Sigma phase (s) was observed only for the failed anchor (Fig.2c) at grain boundaries and at grain interiors. The failed welded end clearly revealed (Fig.3a) the weld solidified zone and a recrystallised fine grain zone adjacent to it. Higher magnification view of the welded zone showed (Fig.3b) presence of delta (d) ferrite. Grain boundary cracks were noticed (Fig.3c) in coarse grained HAZ adjacent to the weld and these cracks were actually formed along the continuous network of grain boundary carbide precipitates

Table 1. Chemical composition of the anchor material

Element	Observed level (% Wt.)		Specified level for AISI 309 SS (% Wt.)
	Failed anchor	unexposed anchor	
Cr	17.70	17.91	22-24
Ni	11.45	11.66	12-15
C	0.143	0.144	0.20 (max.)
Mn	0.11	0.22	2.00
P	0.02	0.02	0.045
S	0.013	0.012	0.030
Si	0.88	0.21	0.75
Fe	balance	balance	balance

Table 2. Hardness test results

Sample ID	HV_{30}
New anchor rod	157
Service exposed & failed anchor rod	186

Table 3. Tensile properties of failed and unexposed anchor samples

Specimen ID	0.2% PS, MPa	UTS, MPa	% El (GL=15mm)	% RA
Failed anchor	305	667	43	40
Unexposed anchor	268	625	72	72
Specification level	230 (min)	550-750	30% (min. for 25mm GL)	---

4.4.1. Optical Microscopy

Optical micrographs of unexposed and failed anchors were shown in Fig. 2. Observed microstructure is typical of a austenitic stainless steel. Only failed anchor material showed (Fig. 2c) grain boundary carbides along with sigma phase at the grain boundaries and at the grain interior. The failed welded end clearly revealed (Fig.3a) the weld solidified zone and a recrystallised fine grain zone adjacent to it. Higher magnification view of the welded zone showed (Fig.3b) presence of delta (d) ferrite. Grain boundary cracks were noticed (Fig.3c) in coarse grained HAZ adjacent to the weld and these cracks were actually formed along the continuous network of grain boundary carbide precipitates.

4.4.2 Electron Microscopy

Scanning electron microscope was used to analyse the microstructure of failed and unexposed anchor materials. Much of the fracture surface got oxidised due to exposure to operating environment. A proprietary cleaning solution was used to remove the oxide layers. Fractured surface from the welded sided of the failed anchor showed several different features (Fig.4a). Though the oxide layers did not get removed fully, observed features (Fig.4b) fairly indicates that the fracture is mostly of intergranular type. Few cracks were also visible. Fractographic examination of tensile tested samples showed a brittle intergranular fracture for sample from failed anchor (Fig.5a). Unexposed anchor samples showed (Fig.5b) intergranular but with ductile features of void coalescence on the grain facets. EDX spectra analysis from a spot on fracture surface for tensile sample from failed anchor confirmed presence of sigma (s) phase.

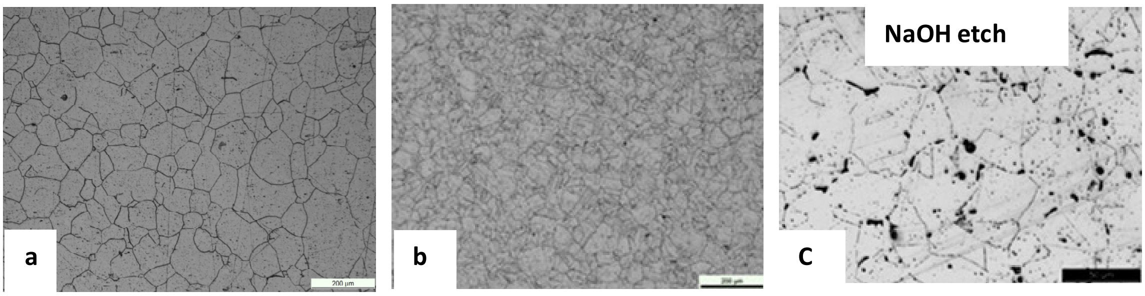


Fig.2. Optical micrographs of anchors (a) unexposed (b) and (c) failed. Sigma phase seen as dark precipitates after electrolytic etching with NaOH

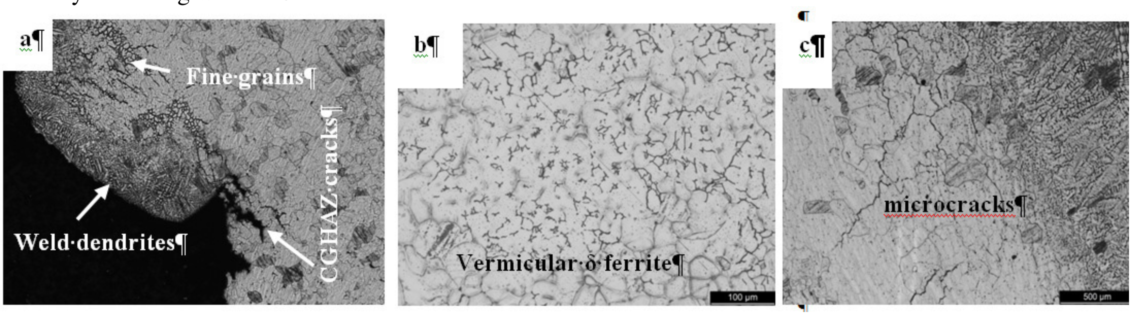


Fig.3 Optical micrographs of longitudinal section of failed anchor welded end side (a) weld solidified area with fine and coarse grain areas (b) delta ferrite in the fine grain area (c) microcracks along the coarse grain boundaries

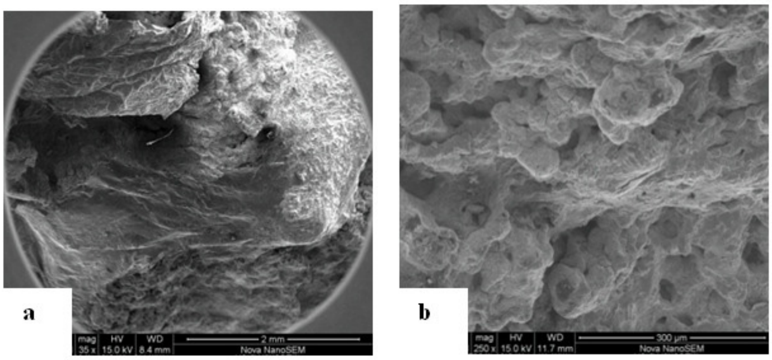
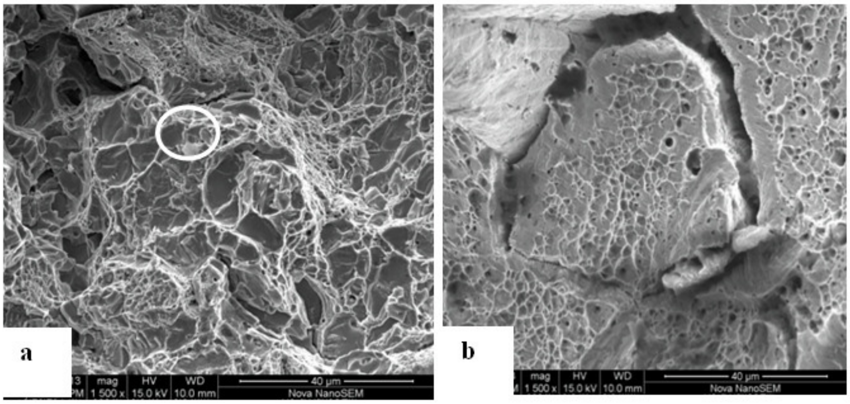


Fig.4 Electron micrographs of the failed anchor - welded side end

5. Discussion

Failure of refractory without any significant damage to it is a common occurrence in boiler applications. Failure of the anchor rod is the main reason for such happenings. Failure often caused by defects in the weld like improper use of weld consumables (electrodes, filler wire), non-standard weld procedures/ practices, formation of deleterious phases in the weld, cracks in the weld zone caused during welding , lack of fusion and lack of penetration of weld [3-5].



Element	*Wt %*
C K	00.63
SiK	00.31
CrK	30.16
FeK	59.10
NiK	05.83

Fig.5. Fractographs of tensile tested samples (a) failed (b) unexposed. EDX analysis of encircled spot given by the side.

Improper material selection in terms of high temperature strength and corrosion resistance to service environment is also a reason for SS anchors failure [5] . In the present case, base material selection is correct as austenitic AISI309 grade is a widely recommended one particularly when welding with mild steel is involved [4]. However, analysed chemical composition of failed anchor fell short of the range specified specifically for chromium (Cr), nickel (Ni) and manganese (Mn) levels. Silicon, a ferrite stabilizer which promotes sigma phase formation, is marginally higher (0.88%) than the specified level (0.75%).

In the refractory linings, it is possible that a thermal profile exist in which a portion of the lining and anchor rods get exposed to the s- phase forming range [1-3]. Embrittlement by s- phase formation occurs when austenitic stainless steel is held in the temperature range 565-850^{o}C either in service or when slowly cooled in this range for prolonged periods. s- phase reduce the toughness, creep and fatigue strength. At higher temperature service embrittlement effect of s-phase is not effective. However, at temperatures below 200^{o}C, it makes a more significant impact on the life of the component. More frequent shutdowns and shock loading will result in brittle failure of component material in presence of s- phase.

In the present failure, s- phase presence was identified (Figs.2c&5b). Being a hard intermetallic phase, presence of s-phase can be indicated by lower ductility, lower impact strength and increased hardness compared to that in unexposed condition. s-phase presence reflected on hardness (Table 2) and on tensile ductility (Table 3). Due to non-availability of enough material, impact tests could not be carried out. Fractographs (Figs. 4&5) further confirms it. If inadequate expansion joint exist, opening of refractory joints and entry of hot flue gases in between the refractory joints may occur to heat up the refractory and anchor rods well above the permitted range. This effect may also extend the size of the s- phase prone zone. Plant reported inadequate expansion joint and damage to backup insulation layer. Appearance of buckled outer shell with burn marks at the failed refractory location further confirms this fact. Oxidised nature of the cracked/fractured surface, erosion of the surface at one side of the rod confirms that embedded rods got exposed to hot flue gases. From these points, it is clear that the failure at the non-welded end of the anchor happened due to s- phase embrittlement caused by thermal exposure in the s- phase formation range. Frequent thermal load disruptions due to shutdowns caused shock loading of the anchor and thus s-phase embrittlement induced cracking occurred leading to lesser support for the refractory which subsequently failed.

The failure of anchor rod at the SS–MS welded end side occurred in the weld zone was confirmed by microstructural observations (Fig.3). Presence of s- phase, d-ferrite, continuous network of carbide at the grain boundary, microcracks in CGHAZ all points to a poor quality of weld. Non-availability of a service exposed but un-failed SS-mild steel weld for investigation and information on the weld consumables, welding method made decision on the exact cause of primary weld failure of the anchor rod a little bit difficult. In the refractory industry it is commonly observed that there is no written weld procedure which is qualified by tests like composition analysis, mechanical properties testing and corrosion testing. As per specifications [4], for welding AISI309 SS to mild steel, low carbon 309S electrode is recommended to balance weld composition to have δ ferrite content of 2.5-10%. Less than 2% ferrite will result in micro cracking of weld and excess of 10% δ ferrite, formation of s-phase and consequent embrittlement problem have to be faced up on. Since no information on the consumable is available, final ferrite content in the weld could not be predicted. Vermicular d-ferrite can form when a Cr- rich stainless steel like AISI309 solidified as primary d-ferrite. Subsequent cooling in the d-ferrite - austenite region, Cr-rich core region of the dendrite result in vermicular ferrite while Cr-low outer region transforms to austenite. Appearance of vermicular ferrite in weld (Fig.3b) is thus normal. Considering the shorter life of 3 years, carbon migration related degradation can be ruled out.

Damage to the backup insulation layers and buckling of the outer shell at the hot face area clearly show that the mild steel plate to which the anchors have been welded had experienced overheating to temperatures than allowed by design. This may definitely lead to lower strength of the MS plate which in turn reflect as MS-SS weld failure. Once the anchor support fails, refractory panel is left with loss in reinforcement and eventually it will fall down. Straightening of anchors is further indication that a higher temperature than design permitted values have been experienced resulting in loss in strength for the metallic anchor which got deformed under the refractory weight at such temperatures

6. Conclusions

Weld zone is of poor quality with formation s- phase and microcracks along the continuously precipitated grain boundaries, intergranular cracking at coarse grain HAZ. Inadequate expansion joint resulted in entry of flue gas into the gap between the refractory panel and damaged backup insulation which consequently resulted in buckling of outer shell due to over temperatures. At such higher temperatures, decrease in strength of the SS anchor - MS plate weld and associated poor quality of weld resulted in failure of the anchors at the weldment and loss of reinforcement support resulted in falling of refractory panel portions. At the non-welded end of the anchor rod cracking due to s-phase formation which led to further weakening of the refractory reinforcement and contributed to the refractory failure.

References

1. Paul A Plater and Graham Quigley, J. Aust. Ceram. Soc. 43 No.2 (2007) pp120-124
2. Kurt Knitter, Care and Maintenance of Circulating Fluidized Bed Boilers Refractory Failure, www.nasoe.com
3. G.Palmer and K.C.Tan, Refractories and applications news 14 No.4 (2009) pp 5-16The Avesta welding manual-Practice and products for stainless steel welding, (ed.) Martin Laren, Avesta Welding (2004)
4. High temperature characteristics of stainless steels, A designer's handbook series no.9004, American iron and steel institute